Final Technical Report

Award Number G13AP00076

Site Response and Soil Amplification in the National Capital Region During the 2011 Virginia Earthquake - Development of Region-Specific Site Amplification Factors

C. Guney Olgun[1], Martin C. Chapman[2], James Martin[3], Mark Tilashalski, Adrian Rodriguez-Marek, Elizabeth A. Godfrey, Sharmin Shamsalsadati, and Morgan A. Eddy

[1]Department of Civil and Environmental Engineering
Virginia Polytechnic Institute and State University
200 Patton Hall
Blacksburg, Virginia, 24061 (GO)
email: olgun@vt.edu, telephone: (540) 231-2036

[2]Department of Geosciences
Virginia Polytechnic Institute and State University
4044 Derring Hall
Blacksburg, Virginia, 24061 (MC)
email: mcc@vt.edu, telephone: (540) 231-5036

[3]Glenn Department of Civil Engineering
Clemson University
Lowry Hall
Clemson University
Clemson, South Carolina (JM)
email: jrmart@clemson.edu, telephone: (864) 656-3002

Project Period: September 2013 - May 2015

Abstract

The project assembled a geotechnical data set and conducted site response analysis at 62 sites in the Washington, DC area to investigate the role that shallow geological conditions played in spatial variation of ground shaking during the 23 August, 2011, Mineral, Virginia, earthquake. The results exhibit large values for the short-period site amplification factor, F_a, implying serious insufficiencies in current NEHRP design guidelines for site amplification when applied to the National Capital Region. Strong impedance contrasts due to shallow intact rock lead to increased ground shaking, especially at short periods. As a result, Washington, D.C. is exposed to greater than anticipated shaking intensity at the ground surface in the event of earthquakes.

Introduction

Many sites in the Washington, DC area experienced strong ground shaking and attendant structural damage during the M 5.7, 23 August, 2011 Mineral, Virginia earthquake (Horton et al. 2015). Intensity data show an increase in ground motion amplitude to the northeast of the epicenter, particularly in the Washington D.C. - Baltimore areas, and around Chesapeake Bay. The intensity observations suggest a combination of effects, including anisotropic wave propagation in the crust and site response (Hough, 2012). In regard to site response, Washington D.C. is situated astride the Fall Line, which marks the boundary between the Appalachian Piedmont geologic province and the Atlantic Coastal Plain. The northwestern half of the district is in the Piedmont, were hard Paleozoic crystalline rock is either exposed at the surface or found at relatively shallow depths beneath alluvium or residual soils. The southeastern part of the District is in the Coastal Plain, where the shallow subsurface is comprised of sands, clays, silts and gravel deposits of the Cretaceous Potomac formation. The sediments rest upon crystalline rocks of the Piedmont province. One would expect substantial differences in ground shaking intensity in different parts of the Washington, DC area due to the differences in the shallow subsurface conditions.

The project assembled a geotechnical data set and conducted site response analysis to investigate the role of shallow geological conditions played in spatial variation of ground shaking in the Washington, D.C. area during the Mineral Earthquake.

Data and Analysis

Figure 1 shows an idealized geologic cross-section through Washington, D.C., with the Piedmont to the west and Coastal Plain to the east divided by the Fall Line. In the Piedmont, hard Mesozoic and Paleozoic crystalline rock is close to the ground surface. Residual soil and saprolitic formations, usually up to 30 meters in thickness and Quaternary in age, overlie rock at most locations. Thickness of the weathered zone is uncertain but estimated to be between 20-50 meters (with extreme limits of 0 and 500 meters) and underlain by competent Mesozoic and Paleozoic rock with shear wave velocity of at least 2,500 m/s (Obermeier and Langer 1986, Darton 1950, Reed and Obermeier 1982). Along the Fall Line, subsurface profiles are similar with an upper layer comprised of Quaternary and Tertiary alluvial soils and saprolitic residual soils that overlie the rock formation. In the vicinity of the Fall Line, the conditions are highly variable, depending on elevation and distance from major streams. To the east of the Fall Line, alluvial soils overlie eastward-thickening Coastal Plain sediments of Cretaceous age (Potomac

Formation), which in turn overlie weathered crystalline rock. For both physiographic provinces and along the Fall Line, geologic unconformities create sharp impedance contrasts between formation boundaries (i.e. saprolite/rock, alluvial/Potomac Formation/rock). The sharp impedance contrasts can potentially result in significant seismic amplification not accounted for in the current building codes.

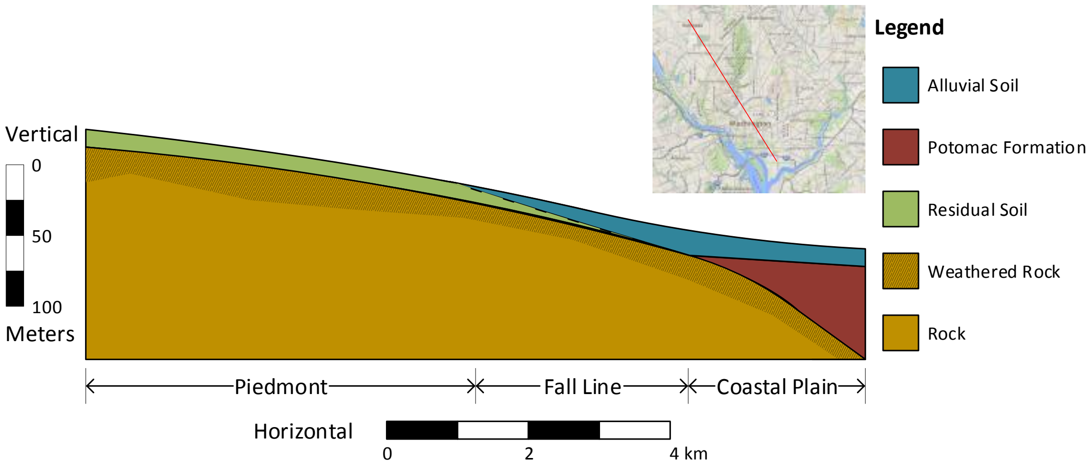

Figure 1: **Geologic Cross-Section of Washington, D.C. Running NW to SE**

Site investigation information was provided by numerous engineering firms in the study area. Available data for each site included boring logs from geotechnical site investigations, ReMi and MASW measurements of shear wave velocity, and SPT measurements. Figure 2 shows an aerial map of studied sites, limited to a small area for clarity purposes. Also included is an approximate location of the Fall Line separating the Piedmont and Coastal Plain regions. Points A, B, and C indicate the approximate location of representative sites for the Piedmont, Fall Line, and Coastal Plain, respectively.

Each site was divided into sublayers based on geologic unit (Potomac Formation, alluvial soil, and residual soil) and soil index properties. Then, each sublayer was assigned a value for depth, overburden stress, SPT blowcount, and shear wave velocity based on the average of each measurement through the entire sublayer. Next, each average value became a data point in a database of properties for each geologic unit. With this database, the authors developed statistical relationships between depth, overburden stress, SPT blowcount, and shear wave velocity for each geologic unit. These relationships were a useful decision-making tool for site analysis.

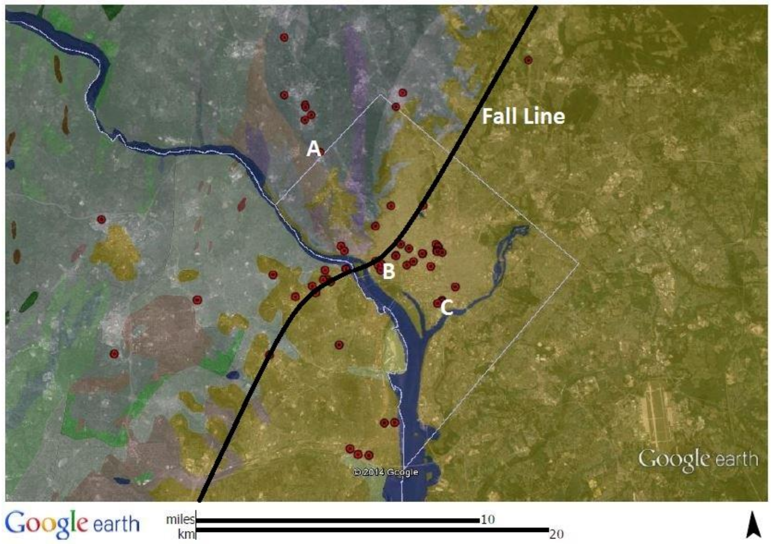

Figure 2: Aerial Map of Studied Sites

A shear wave velocity model was developed for each site, extending from the ground surface down to reference rock at V_s = 3500 m/s. Figure 3 shows V_s profiles for three sites representative of conditions in the Piedmont, in the Coastal Plain near the Fall Line, and further southeast into the Coastal Plain. For each site, measured shear wave velocity values extend to approximately 30 m depth. For both the Piedmont and Fall Line sites where weathered rock is encountered during the site investigation, shear wave velocity was increased to 2000 m/s as a gradient in accordance with the recommendations given in Hashash et al (2014). For the Coastal Plain region where rock is not encountered in site investigation, the depth to bedrock was taken from a map provided in Darton (1950). Shear wave velocity in the Potomac Formation was modeled to increase at 5 m/s/m up to 750 m/s based on the relationship between V_s and depth in the Potomac Formation.

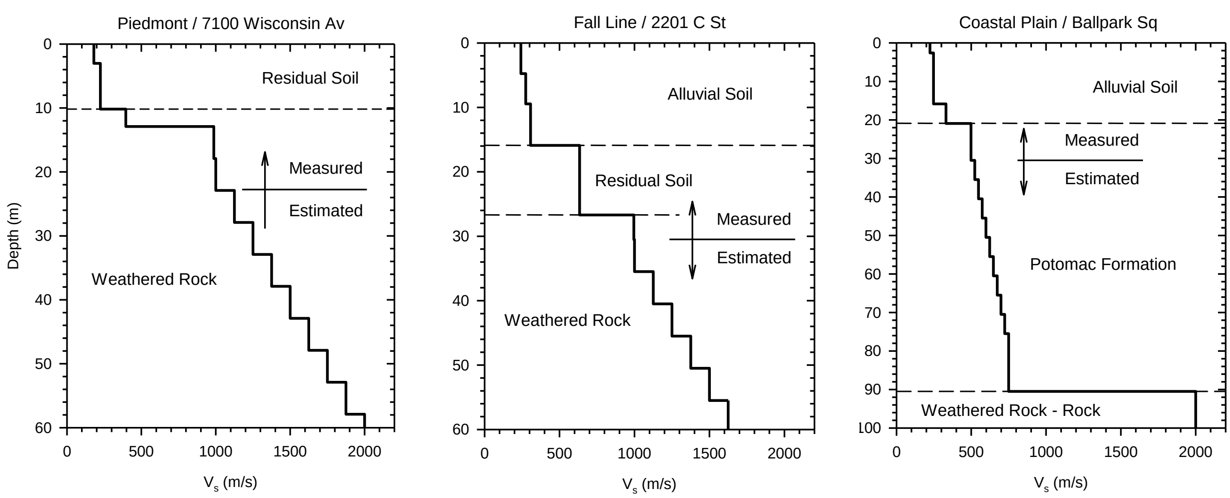

Figure 3: Shear Wave Velocity Profiles for Representative Sites in Each Region

One-dimensional site response analyses were performed for each site. These computations assume vertically incident S waves, with strain-dependent material properties, and use the standard procedure of Schnabel et al. (1972). The synthetic input ground motion assumed in this example is a M_w 6.5 earthquake at 150 km with a stress drop of 100 MPa, developed using the stochastic model, with ω^{-2} source spectrum and path attenuation according to Atkinson and Boore (1995). Analyses were performed using the program Deepsoil (Hashash 2012). Shear modulus and damping ratio curves developed by Ishibashi and Zhang (1993) were used for all soil layers. The bedrock was assumed to be an infinite half space with a damping ratio of 0.03%, and 40 iterations were specified for each analysis.

Results

Figure 4 shows the plotted ground motion response spectral acceleration for all 62 sites, according to region. Individual site response spectra are plotted in gray. Dashed black lines show the median and 16th and 84th percentile response spectra. Piedmont sites exhibit the greatest spectral acceleration at very short periods (< 0.1 seconds) and considerable acceleration in the short period band (0.1 – 0.5 seconds). Fall Line and Coastal Plain sites experience maximum spectral acceleration in the short period band. Additionally, Coastal Plain sites display greater spectral response for mid-to-long periods (> 0.5 seconds) than either of the other regions.

Figure 5 shows the computed short period site amplification factor, F_a, for all 62 studied sites. F_a is computed as the average ratio of response spectra (*RRS*) between the ground surface and a soft rock layer at the B-C boundary over the period range from 0.1 – 0.5 seconds. Marker style indicates the site region and error bars indicate one standard deviation range of *RRS*. The marked line indicates the amplification factor values recommended by NEHRP and contained in the building code. This figure shows that for all sites, regardless of region, computed short period amplification factors were on the order of two to three times greater than the values recommended for design. For most sites, even the low end of the *RRS* range exceeds recommended values. This is indicative of shortcomings in design guidelines.

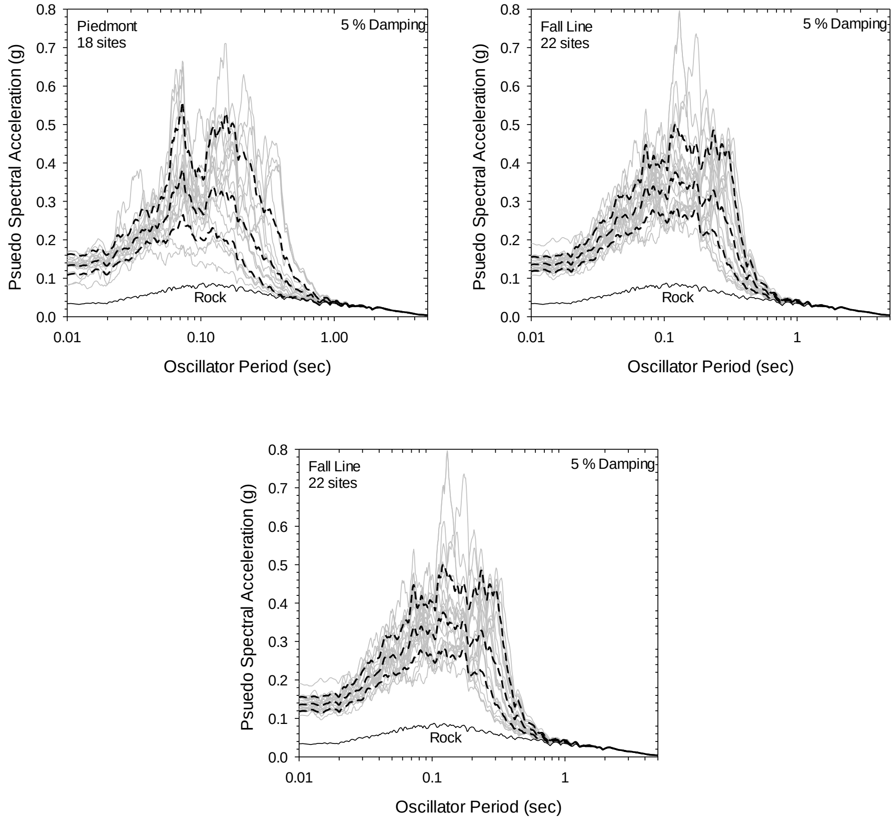

Figure 4: Ground Response Spectra for Studied Sites

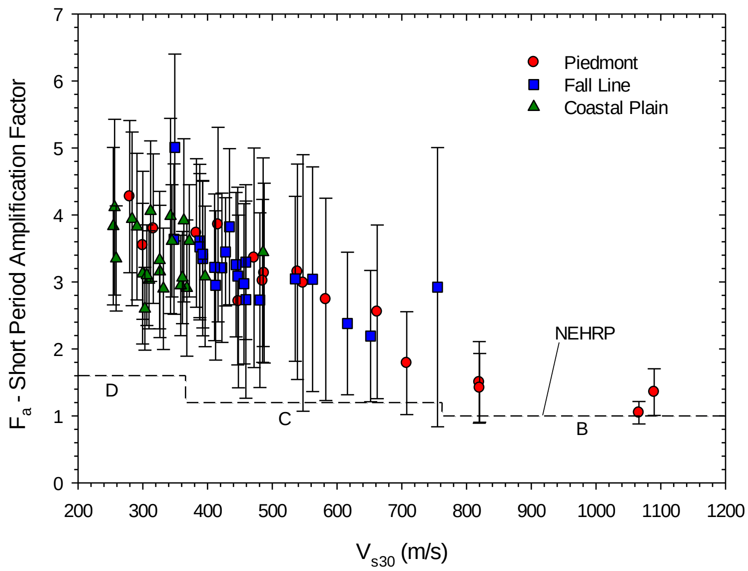

Figure 5: Computed F_a for Studied Sites

Figure 6 shows a similar plot for the mid-to-long period amplification factors, F_v. Unlike the previous plot, the computed amplification factors typically fall within the boundary provided by building code recommendations. Sites located in the Coastal Plain are most at risk of exceeding design guidelines. The *RRS* for some Fall Line and most Piedmont sites is nearly constant. This is reflected in Figure 4, which shows that response spectra for these regions are nearly constant at periods longer than 0.5 seconds.

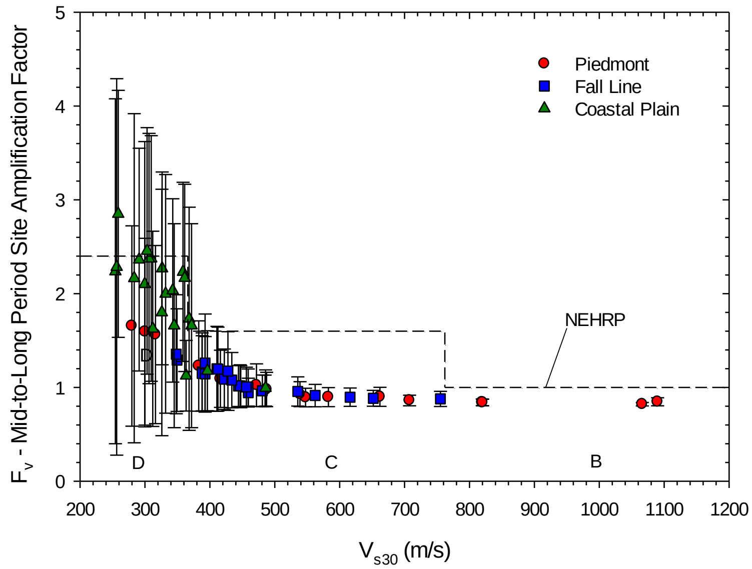

Figure 6: Computed F_v for Studied Sites

Conclusions

Site response analysis was performed for 62 sites in the Washington, D.C. area. Large computed values for short-period site amplification factor, F_a, indicate gross insufficiencies in current NEHRP design guidelines for site amplification when applied to the NCR. The authors believe sharp impedance contrasts due to shallow intact rock lead to increased ground shaking, especially at short periods. As a result, Washington, D.C. could be exposed to greater than anticipated shaking intensity at the ground surface in the event of an earthquake. Due to the city's role as both a major population hub and the center of United States government, structural failure in the area could have multiplied human and economic losses.

Additionally, similar results could occur in other metropolitan areas in the CEUS. For instance, the results of similar research performed around Columbia, SC agree with the results of this study (Olgun et al. 2014). Taken further, other major population centers along the Fall Line such as Philadelphia, PA, Baltimore, MD, Richmond, VA, and Raleigh, NC could be at risk.

The results of this study, combined with the lack of information on the effects of earthquakes in the CEUS, indicate the need for further study in this field and the potential need for revision of current site amplification design guidelines in order to better account for CEUS geology. Additional work is needed to explore the relationship between seismic amplification and various site parameters (such as impedance contrasts) in the CEUS. Additionally, improved deep rock shear wave velocity measurements are needed to refine the model assumptions made in this study.

References

Atkinson, G.M. and D.M. Boore, (1995). "New ground motion relations for Eastern North America." *Bulletin of the Seismological Society of America*. 83, 1778-1798.

Darton, N.H. (1950). "Configuration of the bedrock surfaces of the District of Columbia and vicinity," *USGS Professional Paper 217*.

Hashash, Y.M.A (2012). "DEEPSOIL V5.1 – User Manual and Tutorial," Department of Civil and Environmental Engineering – University of Illinois at Urbana-Champaign.

Hashash, Y.M.A., A.R Kottke, J.P. Stewart, K.W. Campbell, B. Kim, C. Moss, S. Nikolaou, E.M. Rathje, and W.J. Silva (2014). "Reference rock site condition for central and eastern North America." *Bulletin of the Seismological Society of America*, 104, No. 2, April.

Horton, J.W., Jr., M.C. Chapman, and R.A. Green (2015). "The 2011 Mineral, Virginia, earthquake, and its significance for seismic hazards in eastern North America—Overview and synthesis," in *The 2011 Mineral, Virginia, Earthquake and its Significance for Seismic Hazards in Eastern North America*, Horton, J.W., Jr., Chapman, M.C., and Green, R.A., (Editors), *Geological Society of America Special Paper 509*, 1-26.

Hough, S.E. (2012). "Initial assessment of the intensity distribution of the 2011 Mw 5.8 Mineral, Virginia, earthquake," *Seismological Research Letters*, 83, no. 4, 649-657.

Ishibashi, I. and X. Zhang (1993). "Unified dynamic shear moduli and damping ratios of sand and clay," *Soils and Foundations*, Vol. 33, No. 1, pp. 182-191.

Obermeier, S.F and W.H. Langer (1986). "Relationships between geology and engineering characteristics of soils and weathered rocks of Fairfax County and Vicinity, Virginia." *USGS Professional Paper 1344*. 30pp.

Olgun, C.G., Eddy, M.A., Godfrey, E.A., Chapman, M.C., Tilashalski, M., Martin, J.R. and Camp, W. (2014). "Investigation of Seismic Site Amplification for Non-NEHRP Site Conditions: Site Response Study of Columbia, SC." *GeoCongress 2014*, American Society of Civil Engineers.

Reed, J.C. and S.F. Obermeier (1982). "The Geology beneath Washington, D.C. – The foundations of a nation's capital." *Geological Society of America Reviews in Engineering Geology*, Volume V, p27-50.

Schnabel, P.B., Lysmer, J., and Seed, H.B. (1972). "SHAKE: A Computer Program for Earthquake Response Analysis of Horizontally Layered Sites," *Report No. UCB/EERC-72/12*, Earthquake Engineering Research Center, University of California, Berkeley, December, 102p.